PROBING THE WARM DARK MATTER WITH HIGH-Z QUASAR LUMINOSITY FUNCTION

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Draft version August 6, 2009

ABSTRACT

In a warm dark matter (WDM) cosmology, the first objects to form at $z \geq 20$ are one dimensional filaments with mean length on the order of the WDM free-streaming scale. Gao and Theuns recently claimed by using high-resolution hydrodynamic simulations that the eventual collapse of these WDM filaments along their longest axes may seed the supermassive black holes that power high-z quasars. In this picture, it is supposed that the high-z quasar luminosity function should reflect how abundant the WDM filaments are in the early universe. We derive analytically the mass function of early-universe filaments with the help of the Zel'dovich approximation. Then, we determine the rate of its decrease in the mass section corresponding to the free streaming scale of a WDM particle of mass m_ν. Adjusting the value of m_ν, we fit the slope of the analytic model to that of the high-z quasar luminosity function measured from the Sloan Digital Sky Survey DR3. A new WDM constraint from this feasibility study is found to be consistent with the lightest super-symmetric partner.

Subject headings: cosmology:theory — large-scale structure of universe

1. INTRODUCTION

The large-scale features of the observed universe are strikingly consistent with the theoretical predictions based on the cold dark matter model. The combined analyses of the recent data from the observations of cosmic microwave background (CMB), galaxy power spectrum and Type Ia supernovae (e.g., Dunkley et al. 2009, and references therein) have been capable of measuring the key cosmological parameters that characterize the CDM model with surprisingly high precision. This has opened an era of precision cosmology, echoing the triumph of the CDM model.

Nevertheless, the status of the CDM model as the standard paradigm has been shaking currently in both observational and theoretical perspectives. Observations have reported several mismatches between the predictions of the CDM model and the real phenomena on galactic and subgalactic scales. For instance, the abundance of galactic satellites, the slope of the inner core of the dark halo density profiles, and the degree of void emptiness have exhibited apparent conflicts between theory and observation (Klypin et al. 1999; Moore et al. 1999; Peebles 2001). Very recently, Disney et al. (2008) measured the cross-correlations between different galaxy's observables and showed that only a single parameter suffices to explain the complex structures of galaxies. This phenomenon is inconsistent with the CDM picture where the galaxy formation is driven by hierarchical merging process. Although it is still inconclusive whether the reported mismatches really indicate the failure of the CDM model or they are just by-products of the selection effects and/or limitations of the observational techniques, it has certainly led to an emergence of alternative models.

A theoretical challenge comes from the fact that the extension of the standard particle physics favors the warm dark matter (WDM) rather than CDM. The WDM differs from CDM in a respect that the WDM particles have non-negligible free streaming scale, l_ν. On scales larger than l_ν, WDM behave just like CDM. On the other hand, on scales less than l_ν, WDM do not cluster but free stream due to their large velocity dispersions unlike CDM which cluster on all scales. It is this property that enables the WDM model to overcome the observational mismatches faced by the CDM model. The list of realistic WDM candidates that have so far proposed includes gravitinos (Bertone et al. 2005, and references therein), axions (Battye & Shellard 1994), and sterile neutrinos (Dodelson & Widrow 1994), each of which has distinct characteristic mass range. By constraining the WDM particle mass, it may be possible to rule out a certain WDM candidate. In fact there have been already such attempts: For instance, Seljak et al. (2006) constrained the particle mass of WDM by using the Lyα forest power spectrum and suggested that the sterile neutrinos be ruled out (see also Viel et al. 2006)

In a WDM universe, the objects that will first condense out in the initial density inhomogeneities are not zero dimensional clumps but one dimensional filaments. Gao & Theuns (2007) recently studied the formation and properties of WDM filaments with high-resolution hydrodynamic simulations, and proposed that the early-universe filaments would seed the supermassive black holes that power the quasars at $z \geq 6$ through their eventual collapse along the longest axes. If this scenario is true, then, the following two issues should be related to each other: How luminous and abundant the first generation high-z quasars are; and how massive and abundant the early-universe WDM filaments are. In statistical terms, the luminosity function of the high-z quasars should be related to the mass function of the early-universe filaments. Given that the mass function of the early-universe filaments depends on the particle mass of WDM (see §2), it implies the possibility of using the high-z quasar luminosity function as a new WDM constraint.

The idealistic way to study the mass function of early-universe filaments and its dependence on the WDM par-

ticle mass is to use the hydrodynamics simulations. However, given the computational costs as well as the current resolution-limit of hydrodynamic simulations, it is adequate and quite necessary to consider an analytic approach as the first guideline. Here, we evaluate analytically the abundance of early-universe filaments and constrain the WDM particle mass by fitting its slope in the WDM particle free streaming scale to that of the high-z quasar luminosity function (Fan et al. 2001) determined from the Sloan Digital Sky Survey Data Release 3 (SDSS) (Trump et al. 2006). For the key cosmological parameters other than the WDM particle mass, we assume a WMAP5 cosmology (Dunkley et al. 2009) throughout this paper.

The plan of this paper is as follows. In §2, an analytic model for the abundance of early universe filaments is presented. In §3, a constraint on the particle mass of WDM is provided by fitting the analytic model to the observational data from SDSS. In §4, the achievements as well as the caveats of our work are discussed.

2. THE ABUNDANCE OF EARLY UNIVERSE FILAMENTS

The Zel'dovich approximation predicts generically and in the most simple way the formation of early-universe filaments (Zel'dovich 1970). According to this model, the mass density ρ of a given region can be expressed in terms of the Lagrangian quantities as

$$\rho = \frac{\bar{\rho}}{[1 - D(z)\lambda_1][1 - D(z)\lambda_2][1 - D(z)\lambda_3]}, \quad (1)$$

where $\bar{\rho}$ is the mean background density, $\lambda_1, \lambda_2, \lambda_3$ (in a decreasing order) are the three eigenvalues of the linear deformation tensor, and $D(z)$ is a linear growth factor. Equation (1) predicts that ρ will diverge at $\lambda_1 = 1/D(z)$. That is, the first collapse will occur when the largest eigenvalue reaches a threshold value, $\lambda_c(z) \equiv 1/D(z)$. The sign of the other two eigenvalues, λ_2 and λ_3, at the moment of the first collapse will determine the dimension of a collapsed object. A one-dimensional filament will form if $\lambda_2 > 0$ and $\lambda_3 < 0$, while the formation of a two-dimensional sheet will occur for the case $\lambda_2 < 0$ and $\lambda_3 < 0$. Since we are interested in the formation of "filaments" that are shown to be most abundant in the early universe filled by WDM (Gao & Theuns 2007), we consider only the filament condition, $\lambda_1 = 1/D(z)$, $\lambda_2 > 0$ and $\lambda_3 < 0$.

The fractional volume $F(M, z)$ occupied by those Lagrangian regions which will condense out early-universe filaments at z on mass scale M can be expressed as

$$F(M, z) = p[\lambda_1 \geq \lambda_c(z), \lambda_2 \geq 0, \lambda_3 \leq 0 : \sigma_M], \quad (2)$$

where $\lambda_c(z) = 1/D(z)$ and σ_M is the rms density fluctuation related to the dimensionless linear WDM power spectrum $\Delta_\nu^2(k)$ as

$$\sigma_R^2 \equiv \int_{-\infty}^{\infty} \Delta_\nu^2(k) W^2(k, M) d\ln k, \quad (3)$$

where $W(k, M)$ represents a sharp k-space filter on mass scale M. We adopt the approximation formula of Bode et al. (2001), $\Delta_\nu^2(k) = \Delta^2(k)\left|T_k^\nu\right|^2$ where $\Delta^2(k)$ is the CDM linear power spectrum. The functional form of the WDM transfer function, T_k^ν is given as

$$T_k^\nu = \left[1 + (\alpha k)^{2\gamma}\right]^{-5/\gamma} \quad (4)$$

where

$$\alpha = 0.048(\Omega_\nu/0.4)^{0.15}(h/0.65)^{1.3}(\text{keV}/m_\nu)^{1.15}(1.5/g_\nu)^{0.29}, \quad (5)$$

$\gamma = 1.2$, m_ν is the WDM particle mass and g_ν is the number of degrees of freedom that equals 3/4 for fermions.

The fractional volume in equation (2) can be obtained by integrating the joint probability density distribution of the three eigenvalues that was first derived by Doroshkevich (1970) as

$$p(\lambda_1, \lambda_2, \lambda_3; \sigma_M) = \frac{3375}{8\sqrt{5}\pi\sigma_M^6} \exp\left(-\frac{3I_1^2}{\sigma_M^2} + \frac{15I_2}{2\sigma_M^2}\right)(6)$$
$$\times (\lambda_1 - \lambda_2)(\lambda_2 - \lambda_3)(\lambda_1 - \lambda_3),$$

where $I_1 = \lambda_1 + \lambda_2 + \lambda_3$ and $I_2 = \lambda_1\lambda_2 + \lambda_2\lambda_3 + \lambda_3\lambda_1$. In the spirit of the Press-Schechter theory (Press & Schechter 1974, hereafter PS), we evaluate the number density of early-universe filaments collapsed at mass scale M as

$$n_{\rm F}(M, z) = \frac{\bar{\rho}}{M}\left|\frac{d}{dM}F(M, z)\right|, \quad (7)$$

where the redshift for the formation of the early-universe filaments is set at $z = 23$, in accordance with Gao & Theuns (2007). In the original PS theory which dealt with the mass function of the clumps, equation (7) had to be multiplied by an additional normalization constant to account for the occurrence of the cloud-in-clouds (Bond et al. 1991). But, for our case the cloud-in-clouds will not occur since the WDM particles just free-stream in the early-universe filaments forming no substructures. Henceforth, we do not have to account for the cloud-in-cloud problem in deriving the mass function of early universe filaments.

The cumulative mass function $n_{\rm F}(> M)$ of early universe filaments can be obtained by integrating equation (7) as $n_{\rm F}(> M) \equiv \int_M^\infty n_{\rm F}(M) dM$. Since our focus is not on the amplitude of the mass function but mainly on its slope, we rescale $n_{\rm F}(> M)$ to have unity as M goes zero. Figure 1 plots the rescaled cumulative mass function $\tilde{n}_{\rm F}(> M)$ at $z = 23$ versus M/M_0 for the case of $m_\nu = 1\text{keV}$ (open circles) and $m_\nu = 10\text{keV}$ (open squares). Here M_0 corresponds to the free streaming mass scale of a given WDM particle. As can be seen, $n_{\rm F}(> M)$ begins to decrease as M becomes larger than M_0. The rate of its decrease at $M > M_0$ depends sensitively on the value of the WDM particle mass m_ν: It decreases more rapidly with M for the case of smaller value of m_ν. It is because the less massive WDM particles have smaller free-stream scales. To quantify the rate of the decrease of $n_{\rm F}(> M)$ at $M > M_0$, we fit $n_F(> M)$ to a power-law $M^{\beta+1}$ (i.e., $n_{\rm F}(M) \propto M^\beta$) in the mass range where $0.1 \leq n_{\rm F}(> M)/n_{\rm F}(> M_0) \leq 1$. In the higher mass section where $n_{\rm F}(> F)$ drops exponentially with M, we expect basically no early universe filaments. As demonstrated by Gao & Theuns (2007), only those early-universe filaments with mass comparable in order of magnitude to the WDM free-streaming scale can form which are in turn related to the first-generation supermassive black holes that power the observed high-z luminous quasars. The higher mass section where $n_{\rm F}(> M)/n_{\rm F}(> M_0) < 0.1$ correspond to the scales order-of-magnitude larger than the free streaming
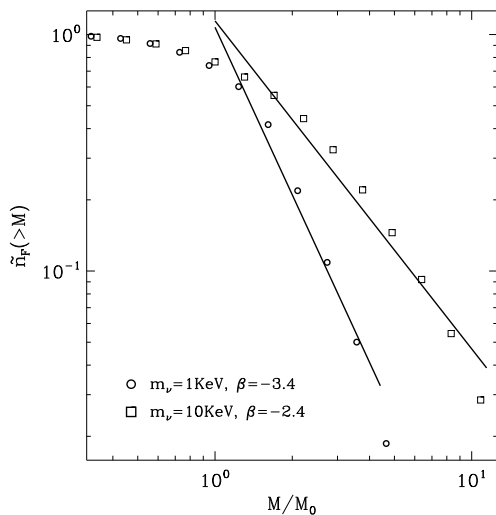
FIG. 1.— The rescaled cumulative mass function of early-universe filaments for the two different cases of WDM particle mass ($m_\nu = 1$ and 10keV as open circles and open squares, respectively). The value M_0 corresponds to the free-streaming mass scale of a given WDM particle. The solid lines represent the power-law fitting in the mass range where $0.1 \leq n_F(> M)/n_F(> M_0) \leq 1$ for the two cases.

scale of a given WDM particles. The solid lines in Fig. 1 represent the power-law fitting of the cumulative mass function of early universe filaments. As can be seen, the slope β indeed depends sensitively on the value of m_ν.

3. RELATION TO HIGH-Z QUASAR LUMINOSITY FUNCTION

The discovery of a supermassive black hole with mass $3 \times 10^9 M_\odot$ in quasar SDSS J1148+5251 at $z = 6.41$ (Willott et al. 2003) has raised a crucial question of what seeded such a supermassive black hole at that early epoch (Podsiadlowski et al. 2003, and references therein). As introduced in §1, Gao & Theuns (2007) have studied the formation of early-universe filaments using high-resolution hydrodynamic simulations for a WDM cosmology and suggested that the ultimate collapse of the WDM filaments along the longest axes should induce vigorous collisions between gas clouds and stars due to their high densities, which would in turn seed the formation of supermassive black holes that power quasars at $z \geq 6$. In subsequent evolution, the black holes would grow active by accreting baryonic gases and dark matter particles that constituted their parent filaments. In this picture, the number density of active black holes at high redshifts would be related to that of early universe filaments.

The luminosity function $\phi(L)$ of high-z quasars at $z \geq 4$ was determined by Fan et al. (2001), who showed that $\phi(L)$ can be well approximated as a power law with high-end slope in the range of -2.5 ± 0.25. If these high-z quasars are indeed powered by the first-generation supermassive black holes formed through the ultimate collapse of the WDM filaments, the high-end slope of the high-z quasar luminosity function should be consistent with the power-law slope of the mass function of early-universe filaments determined in §2. Varying the value of m_ν, we determine the power-law slopes of the mass function of early-universe filaments β, which are shown in Figure 2. The 1σ and 2σ range of the high-end slope of the high-z quasar luminosity function $\phi(L)$ measured from SDSS
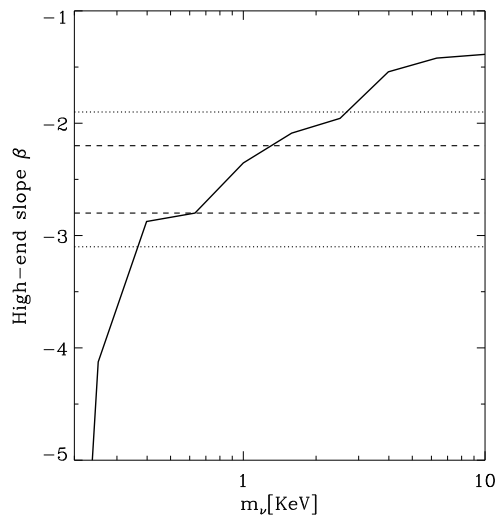

FIG. 2.— The power-law slope of the mass function of early universe filaments versus WDM particle mass. The horizontal dashed and dotted lines correspond to the 1σ and 2σ ranges of the high-end slope of high-z quasar luminosity function determined from SDSS DR3 (Fan et al. 2001),respectively.

DR3 are shown as horizontal dashed and dotted lines, respectively. The comparison indicates that the two slopes agree with each other when m_ν is a few keV.

4. DISCUSSION AND CONCLUSION

Motivated by the recent heuristic work of Gao & Theuns (2007), we have constructed an analytic model for the mass function of the early-universe filaments in a WDM universe. Then we test the possibility of using it as a new WDM constraint. As a feasibility study, we compare the high-end slope of the mass function of the early-universe filaments to that of the high-z quasar luminosity function determined from SDSS DR3 and find a new WDM constraint, $m_\nu \sim$ a few keV. This preliminary result looks consistent with the super-symmetric picture (Bertone et al. 2005). The advantage of the mass function of the early-universe filament as a WDM constraint lies in the fact that the model is purely analytical, free of any fitting or nuisance parameter. It depends only on the WDM particle mass other than the key cosmological parameters. In addition, when the analytic model is compared to the observational result, it is not required to account for any complicated baryon physics since we consider only the *slope* of the mass function.

Yet, there are a couple of simplified assumptions on which our model is based. First, the redshifts of the quasars should be higher than $z \geq 6$ for a more fair comparison. In this work, we just used the redshift range $z \geq 4$, assuming that the quasars at $z \geq 4$ correspond to the first generation. To be more realistic, it will be required to determine the luminosity function of the quasars at $z \geq 6$, but there are only small number of quasars have so far been observed at that high redshift. For example, Vestergarrd et al. (2008) determined the supermassive black hole mass function at $z \geq 4.7$ using a tens of quasars and found the high-end slope in a much larger range of -1.9 ± 1.7, which obviously suffers from large uncertainty due to the small number statistics. Anyway, we would like to mention clearly that the true

high-end slope of the high-z quasar luminosity function is currently significantly more uncertain than the data used here.

Second, the analytic model for the mass function of early universe filaments has to be refined. Our model is the simplest approximation based on the Zel'dovich approximation and the Press-Schechter theory. The validity of our model has to be tested numerically before using it in practice. Third, the evolution of the early-universe filaments has not been taken into account properly for the evaluation of the mass function. In reality, before their eventual collapse at $z \geq 6$, the early-universe filaments may undergo fragmentation due to the tidal effect from the surrounding matter. To account for the evolutionary effects, it will be anyway required to refine the model with the help of the hydrodynamic simulations. Our future work is in this direction.

As a final conclusion, our model and the preliminary result from our feasibility study has provided a proof of concept that the high-z quasar luminosity function will be in principle a useful WDM probe.

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